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REPORT 76-36

Rock, frozen soil and ice breakage by high-frequency electromagnetic radiation

A review

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A review

Pieter Hoekstra

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In the past decade, various workers have investigated the use of high-frequency electromagnetic radiation for breaking and excavating rock and frozen ground. This report reviews the high-frequency dielectric properties of these materials, the physics of heating, and the existing literature on these subjects. The high-frequency dielectric properties of rocks and soils, and the absorption of energy by these materials, are mainly determined by their liquid water contents. Computer modeling was used to calculate absorption energy as a function of distance behind irradiated faces of earth materials. The resulting computations showed that most energy is absorbed in the first few centimeters of frozen ground and weak soils. However, in hard rocks of low water content, electromagnetic waves —

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penetrate more deeply, and significant amounts of energy are also absorbed tens of centimeters behind the irradiated faces. Test results showed that electromagnetic rock breakage is feasible only for excavations in hard rock; test results from the use of electromagnetic radiation for excavating tunnels in weak rocks and frozen ground are not promising.

PREFACE

This report was prepared by Dr. Pieter Hoekstra, Geophysicist, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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The computer modeling of dielectric heating in rocks and soils was performed by Kevin Garner, Dartmouth College, 1976.

This report was technically reviewed by Dr. Malcolm Mellor, Paul Sellmann and Steven Arcone of USA CRREL.

ROCK, FROZEN SOIL AND ICE BREAKAGE BY HIGH-FREQUENCY ELECTROMAGNETIC RADIATION: A REVIEW

Pieter Hoekstra

INTRODUCTION

A series of papers on the use of high-frequency electromagnetic radiation for excavating rocks and frozen ground have appeared in the Russian literature. In many of these publications numerous important details about the experimental parameters, such as temperature, frequency, power and antenna type, and the ground properties, such as compressive strength and mineral type, are missing. In this report the physical principles of heating by high-frequency radiation are reviewed, together with the Russian experience on this subject.

DIELECTRIC HEATING

The amount of heat generated in the ground by an alternating electromagnetic field, and the attenuation of radiation as a function of depth are determined by the dielectric behavior of rocks and soils. The dielectric properties of earth materials vary considerably with the frequency, temperature and composition of the materials.

Soils and rocks are a heterogeneous mixture of different components, such as water, air and mineral matter. The theory of dielectrics attempts to relate the behavior of a heterogeneous mixture to the permittivity of the constituents; the heterogeneous mixture is assigned a single dielectric constant to describe the interactions (e.g., attenuation and reflection) with electromagnetic radiation. The experimental evidence has been that, for soils and rocks, this macroscopic approach is justified well into the microwave frequency range. However, some evidence reviewed on rock breakage by microwave heating suggests that preferential absorption of energy may occur in thin liquid films; therefore, a proper description of the interaction of radiation and matter may need to take into account the unique properties and distribution of the constituents of the mixture.

Two parameters are required to compute the interaction of radiation with matter, the relative dielectric constant K', and the relative dielectric loss factor K''. When a material is placed in an alternating electromagnetic field, there is a current flow in-phase, and one in quadrature phase with the applied voltage: the in-phase current flow is given by

$$j_i = E\omega\epsilon_0 K'' \qquad (1)$$

and the quadrature-phase current flow by

$$j_g = E\omega\epsilon_0 K' \qquad (2)$$

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where j_i and j_g are the in-phase and quadrature-phase current flow, respectively, in amperes/sec

E is the electric field, in volts/m

ω is the angular frequency of the radiation

K' is the relative dielectric constant

K'' is the relative dielectric loss factor

$\epsilon_0 = 8.85 \times 10^{-12}$ farad/m, the permittivity of free space.

The loss tangent is defined by:

$$\tan\delta = j_i/j_g = K''/K'. \tag{3}$$

The in-phase current flow causes dissipation of energy in the form of heat.

The dielectric loss factor K'', in an imperfect dielectric such as earth materials, is the sum of two energy dissipation processes, conduction and relaxation. Conductivity in earth materials is caused by movement of ions, exchangeable ions and dissolved salts. The number of exchangeable ions is roughly proportional to the surface area of rocks and soils, so that clays have higher conductivities than silts and sands, and clay shales and schists have higher conductivities than sandstones and coarse-grained intrusive rocks. Table I shows typical conductivity values for soil and rock types. Dissolved salts in interstitial water are another source of ions, so that the salinity of pore water is also an important factor in determining conductivity.

Conductivity σ is approximately frequency independent and the contribution of conductivity to the dielectric loss at any frequency is given by:

$$K''_c = \sigma/(\epsilon_0\omega) \tag{4}$$

where σ is in mhos/m, and K''_c indicates the part of dielectric loss caused by conductivity.

Relaxation is due to oscillations of the permanent dipole moments of the water molecule in an alternating electric field. Relaxation is frequency dependent and the frequency range in which it occurs is shown in Figure 1. For bulk water the maximum dielectric loss due to relaxation occurs at a frequency of about 2×10^{10} Hz depending on temperature, and for ice between 10^3 and 10^4 Hz. Thus, the total dielectric loss is the sum of loss due to conduction and water dipole relaxation:

$$K'' = K''_c + K''_{rel} \tag{5}$$

where subscripts c and rel indicate the parts due to conduction and relaxation, respectively.

Figure 2 shows the behavior of $K'(\omega)$, $K''(\omega)$, and $\tan\delta$ for a typical soil with a conductivity of 5×10^{-3} mhos/m and a water content of 15% by weight. Below 10^6 Hz, K'' decreases with frequency due to the term $\sigma/\epsilon_0\omega$, and between 10^8 Hz and 10^9 Hz, K'' passes through a minimum, after which the contribution of relaxation becomes important.

A number of parameters influence the dielectric properties of soils and rocks, but the major parameters are soil and rock type, water content and temperature. Figure 3 shows the approximate limits of K'' for weak rocks (e.g., shales and schists) and soils, and strong rocks (e.g., granites and basalts) at temperatures above freezing.[6]

In frozen ground the value of K'' at high frequencies is critically dependent on temperature and the amount of unfrozen water, since liquid water is the only component involved in dipolar relaxation at frequencies above 10^6 Hz. Figure 4 shows K'' for typical frozen soils as a function of temperature at a frequency of 2×10^9 Hz.[6]

Table I. Typical conductivity ranges for soil and rock types.

Soil type	*Unfrozen soil (mhos/m)*	*Frozen soil (mhos/m)*
Clay	10^{-2} to 10^{0}	10^{-2} to 5×10^{-4}
Silt	5×10^{-3} to 2×10^{-2}	3×10^{-4} to 2×10^{-3}
Sand	10^{-3} to 5×10^{-3}	$< 10^{-4}$
Gravel	$< 2\times10^{-3}$	$< 10^{-4}$
Rock types	*Unfrozen rock*	*Frozen rock*
Clay shales	2×10^{-3} to 10^{-1}	
Schist	5×10^{-3} to 10^{-2}	10^{-2} to 5×10^{-4}
Granites	$< 5\times10^{-4}$	

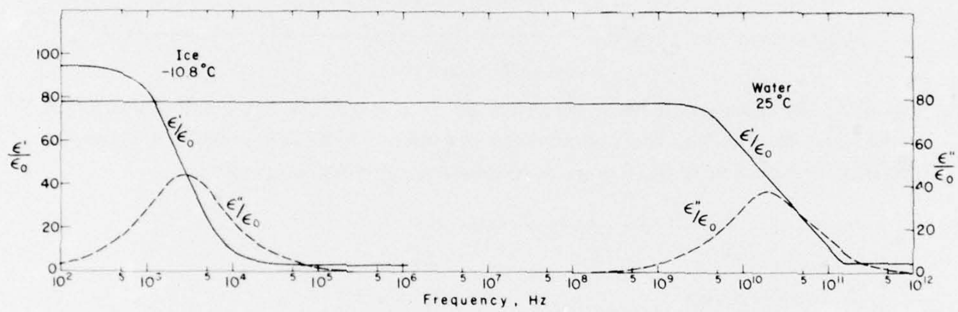


Figure 1. The dielectric relaxation spectra of water and ice. The maximum dielectric loss for water at 25°C occurs at a frequency of about 2×10^{10} Hz. (After Hoekstra and Delaney.[6])

Figure 2. The relative dielectric constant K′, the relative dielectric loss K″ and the loss tangent tan δ as a function of frequency ω for a silty clay soil at a water content of 15% (g H_2O/g soil).

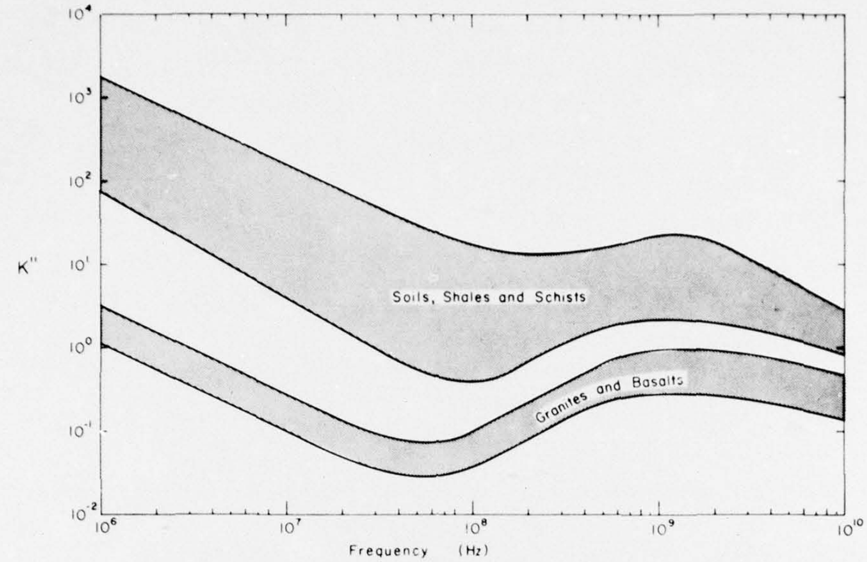


Figure 3. The approximate limits of relative dielectric loss K'' for two broad categories of earth materials. Materials that contain water in excess of 15% (soils, shales, schists) and materials of high density and low water content (e.g., granites and basalts).

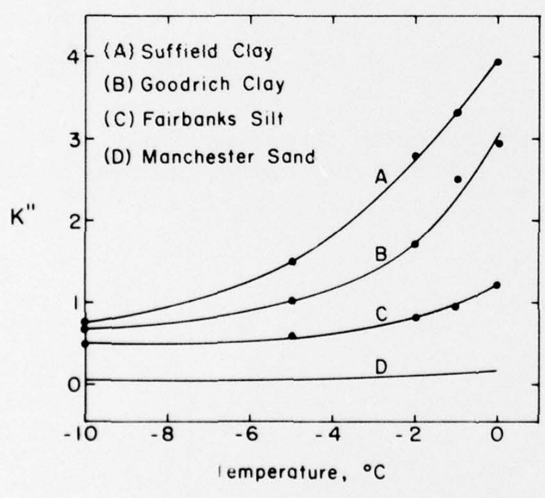


Figure 4. The relative dielectric loss K'' as a function of temperature for several frozen soils at 2×10^9 Hz.

In conventional heating, energy is transferred to the surface of the material to be heated by conduction, convection, or radiation, and into the interior mostly by conduction. In contrast, in dielectric heating, heat is generated directly inside the material, making possible higher heat fluxes that can cause rapid increases in temperature. Dielectric heating implies exposure in an electromagnetic alternating field in the approximate frequency range of 10 to 10^5 MHz, corresponding to wavelengths of 30 m to 0.3 cm.

The following relationships can be derived for the power absorbed per unit volume in a dielectric material:[14]

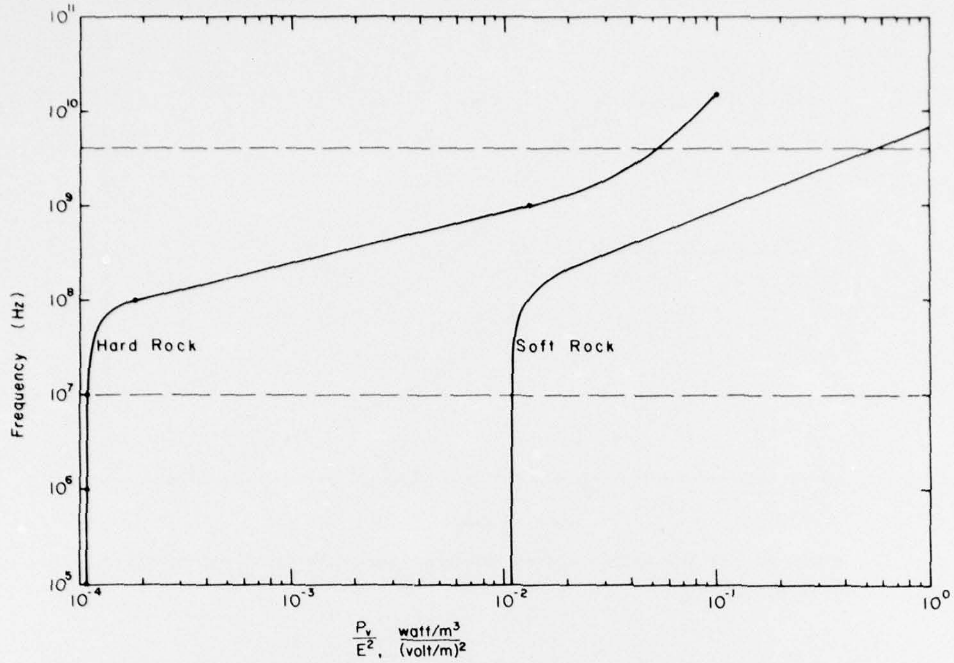


Figure 5. The density of energy absorption from a plane wave (watt/m^3) per unit of field strength square for two broad categories of earth materials as a function of frequency.

$$P_v = 2\pi f \epsilon_0 K''(\omega) E^2 = 5.56 \times 10^{-11} K'' E^2 f \qquad \text{watts/m}^3 \tag{6}$$

where P_v is the power absorbed per unit volume, in watts/m^3
E is field strength, in volts/m
f is frequency, in Hertz
$K''(\omega)$ is frequency dependent.

In Figure 5 the ratio P_v/E^2 (power absorption per unit of field strength square) is plotted as a function of frequency for several earth materials. The amount of heat that can be absorbed by earth materials from an electric field of unit strength rapidly increases at frequencies above 10^7 Hz. There are, however, important tradeoffs in practice in going to higher frequency.

To facilitate an understanding of the physical limitations of dielectric heating in the UHF and microwave frequency range, some of the physical processes of radiation absorption are discussed below. Consider a section of ground partitioned in n horizontal layers of equal thickness. A plane wave propagates vertically downward; the field strength at the surface E_0 is related to the field strength at any depth z, $E(z)$ by:

$$E(z) = E_0 \, e^{-\alpha z} \tag{7}$$

where α is the attenuation coefficient, related to the dielectric constant and loss tangent by:

$$\alpha = \omega/(3\times10^8)\left\{0.5K'\left[\sqrt{1+(\tan\delta)^2}-1\right]\right\}^{1/2} \qquad \text{meters}^{-1} \tag{8}$$

where ω is in radians/sec.

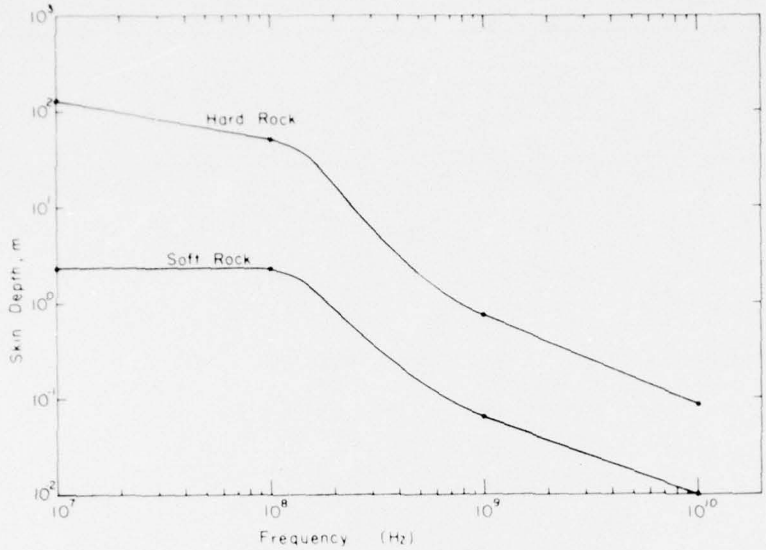


Figure 6. The skin depth as a function of frequency for two broad categories of earth materials.

The depth over which the field strength decays by a factor of 0.37 (= $1/e$) is called the skin depth of the radiation. The skin depth d is equal to $1/\alpha$ meters. In Figure 6 the skin depth is plotted as a function of frequency for hard rock and soft rock. The skin depth of the radiation at 10^9 Hz is thus approximately 1 m for hard rock and less than 10 cm for soft rock.

The power absorbed in each element n per second can be approximated by:

$$P_n = (E_n^2 - E_{n-1}^2)\, 5.56 \times 10^{-11} K'' f \qquad \text{watts/m}^3. \tag{9}$$

The power absorption in each layer causes a temperature rise of:

$$\Delta T_n = (P_n - L_n)/(B_n T) \tag{10}$$

where P_n is the power absorbed in the nth layer
L_n is the rate of heat conduction into or out of the nth layer
$B_n T$ is the heat capacity of the ground in the nth layer at temperature T
ΔT_n is the incremental temperature rise in the nth layer.

The orders of magnitude of values for heat conductivity, heat capacity and coefficient of attenuation α are known, so that the heating of ground by high-frequency radiation can be modeled on a computer. Some critical concepts resulting from computer modeling are shown in Figures 7 and 8 for hard rock and soft rock. In Figure 7 the ratio of the power absorbed at depth z, $P(z)$, and the power absorbed at the surface, $P(0)$, is plotted as a function of depth into the ground for a hard rock (water content less than 5%) and a soft rock (water content more than 5%).

The results show that at 10^8 Hz significant amounts of power are absorbed 10 cm behind the irradiated rock face, in both hard and soft rock, but that at 10^9 Hz the power absorption rapidly falls off with distance. The hard rock in this exercise was assigned a water content of 5% and the difference in power absorption between hard rock and soft rock is about an order of magnitude at

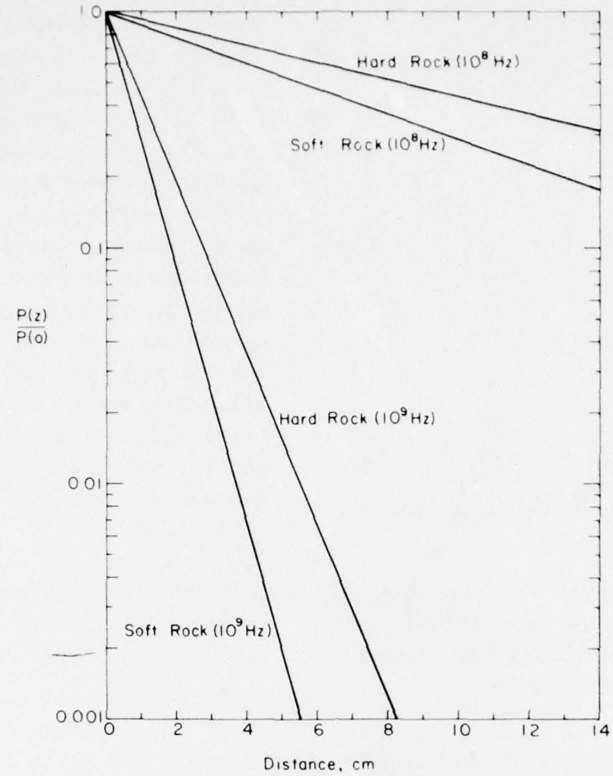


Figure 7. The ratio of power absorbed at depth z, P(z), and the radiated power at the surface, P(0), for two broad categories of earth materials.

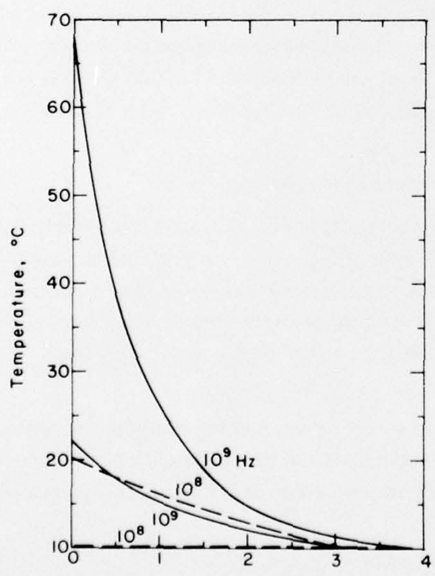


Figure 8. The temperature rise after rock face irradiation by a field of 3 kv/m for 0.4 sec as a function of distance behind the irradiated face. The solid line represents the results for rocks with 10% water; the dotted line represents the results for rocks with less than 5% water.

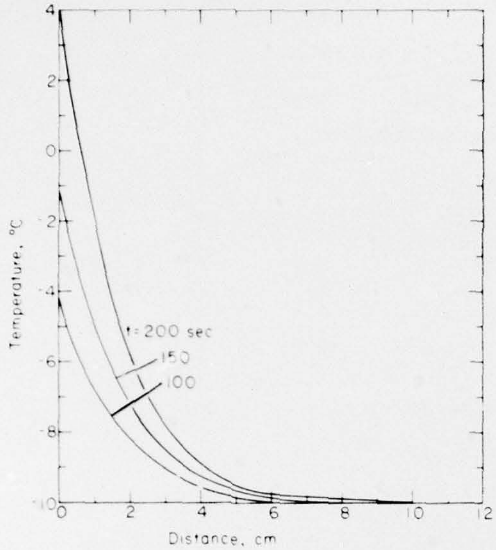


Figure 9. The temperature rise after irradiating frozen Suffield silty clay with 10^9 Hz and a low field strength of 100 v/m as a function of distance behind the irradiated face.

a distance of 5 cm behind the interface. In rocks with water contents less than 5%, the power absorption would fall off less rapidly with distance, and more radiation would penetrate. Figure 8 shows the temperature rise caused by absorption of energy. The results in Figure 8 show that in soft rocks most of the temperature rise takes place in elements within a few centimeters from the surface. In these surface elements, thermal expansion probably occurs freely and probably does not induce fracturing in the interior of the rock. In hard rock, after 0.4 sec, very little temperature rise occurs. In hard rocks, the power is more evenly distributed within the first 20 cm from the surface, and the temperature rise due to absorption of high-frequency energy is also more evenly distributed. In these computations rock is assumed to be a uniform dielectric, and no preferential absorption at particular locations is assumed to take place.

The results in Figure 7 and 8 apply to dielectric heating of soft and hard rocks in the unfrozen state, where probably no major errors are introduced by assuming the physical properties to be independent of temperature. For rocks in the frozen state, the process is more complicated, since all physical properties (dielectric and thermal) become strong functions of temperature (e.g., see Fig. 4). As a result, in frozen ground, which contains unfrozen water, the surface elements heat very quickly in an almost cascading process, since with each incremental temperature rise, the amount of unfrozen water increases, causing more absorption of high-frequency energy. For example, in Figure 9, the relative power absorption in a Suffield silty clay at different times is plotted as a function of depth. To model this behavior, a low field strength was used in the computation, since at high field strength the surface heats up very rapidly. Most energy is absorbed within the first few centimeters from the surface. The penetration of energy can be somewhat improved by lowering the frequency.

The results from modeling described can be summarized as follows:

1. The depth below the surface at which significant amounts of energy are absorbed is critically dependent on the water content of the rock. In hard rocks of high density and low water content, significant amounts of energy penetrate into the first 20 cm. In soft rocks (more than 5% water content), most energy absorption and temperature rise are confined to within 5 cm from the surface. Interior stresses caused by differential thermal expansion can be expected in only hard rocks.

2. In frozen ground of unconsolidated sediments, the heating and melting of surface elements cause virtually all energy to be absorbed in the first centimeter from the surface. In frozen ground, therefore, fracturing caused by thermal stresses cannot be counted on as a mechanism to break rock.

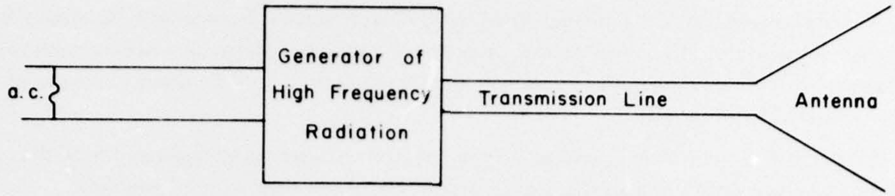


Figure 10. Critical equipment components required for producing high-frequency radiation at a cutting face.

EQUIPMENT USED AT HIGH FREQUENCY

A considerable amount of equipment is required to transform a-c power into radiation of UHF and microwave energy, and to focus the radiation on a particular face. Figure 10 shows a schematic of the critical equipment components. Each of these components places significant restrictions on the frequency and power that can be generated.

High power-generating equipment for industrial purposes is available at 915 and 2450 MHz and in the range of 27 to 40 MHz. Unlike radar applications where pulses are used, dielectric heating requires continuous-wave output. Continuous-wave generators with an effective output of 500 kw in high-frequency energy are about the state of the art. There is a significant (up to 50%) loss in energy in converting a-c energy to energy in high-frequency radiation, and high-power generators often require cooling systems to remove excess heat. The present cost of generating equipment is about $1 to $2 per watt of available microwave power.[1]

The high-frequency energy must be brought from the generator to the radiator at the working face by transmission lines, either coaxial cable or waveguides. The maximum power that can be carried by a transmission line is limited by the dimension and the dielectric strength (breakdown voltage) of the medium of the transmission line carrying the electromagnetic waves. For dry air lines the breakdown voltage is 30,000 v/cm; but in humid environments, such as mines, breakdown may occur at voltages well below the value for dry air.

To transfer 100 kw of power at frequencies above 10^8 Hz requires high-quality coaxial cable of large diameter (e.g., 0.75″ OD, type 573) or waveguides. In either case high-quality components are required to seal all moisture out.

In dielectric heating in the food and paper industry, it is often possible to keep the radiation confined to cavities or transmission lines and place the material to be heated in a cavity (microwave oven), or transport it continuously through a cavity or waveguide (paper industry). In both cases no transitions between transmission lines and free space are required.

On the other hand, for rock breakage, high-frequency energy must always be transferred from transmission line to free space. The device that radiates energy from the transmission line into free space is called the antenna. The impedance of free space is 376 ohms, and the characteristic impedance of a transmission line is typically less than 100 ohms, so that if a transmission line is abruptly terminated much of the power is reflected at the termination. The objective of the antenna is to radiate as much of the energy as possible into free space. An antenna accomplishes this objective by gradually matching the impedance of a transmission line to that of free space, e.g., by tapering a rectangular waveguide into a horn. Efficient radiation requires that the size of the antenna should increase with decreasing frequency (increasing wavelength). For example, the wavelength at 10^8 Hz is 3 m; therefore, an efficient antenna must have characteristic dimensions on the order of 0.75 m (¼ wavelength). This means that at an equant surface the power is radiated over an area on the order of 0.5 m^2.

Radiated power densities (radiated power per unit area) usually decrease with decreasing frequency, because at higher frequency it is easier to focus radiated energy on a work section to obtain large power densities. In a shaft or a tunnel, the size of antennas must be fitted to the size of the tunnel or area to be excavated.

Finally, it should be mentioned that, in many instances, antennas are separated from the rock face by a certain distance and reflections of power take place at the air/rock interface.

REVIEW OF THE LITERATURE

The USSR literature contains a series of manuscripts on the use of electromagnetic energy for excavating earth materials. Many of the manuscripts[9,10,12,13] are based on computations, some of them[8,11,14] describe the results of tests under laboratory conditions, and one manuscript[4] details the results of tests in a working mine.

First, an attempt will be made to summarize the general conclusions that can be drawn from the research to date:

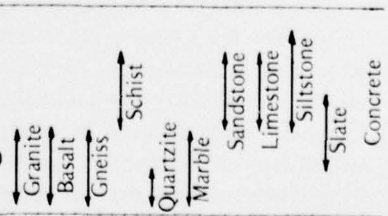
1. The amount of cracking and fracturing introduced in rock upon radiation by electromagnetic energy is strongly dependent on rock type; in rock with compressive strengths in excess of 1000 kg/cm^2, the breakage upon radiation by electromagnetic energy is most pronounced. In general, rocks with a compressive strength greater than 1000 kg/cm^2 are intrusive rocks, as is illustrated in Table II, which shows the range of compressive strength encountered in various rock types. Also, in other methods of applying heat to introduce thermal cracking (flame-jet, laser, electron beam), thermal spalling is most pronounced in hard, unfractured rocks.[2]

2. The results of tests performed on frozen ground appear to imply that in frozen ground best results are achieved by the combined effect of mechanical action and electromagnetic radiation. The fracturing and breakage observed in strong, consolidated rocks have not been observed in frozen ground of unconsolidated sediments.

3. Laboratory tests on a specimen of multicrystalline ice showed melting, due to absorption of electromagnetic energy, at the grain boundaries, followed by disintegration of the ice specimen into individual crystals.

Table II. Classification of rock materials based on unconfined compressive strength (from Hawkes and Mellor[5]).*

Range of U.C.S. (dry samples†)				Range of strength of some common rock materials
Term	*Abbreviation*	*$lbf/in.^2$*	*kgf/cm^2*	
Very weak**	VW	< 1,000	< 70	
Weak	W	1,000-3,000	70-200	
Medium strong	MS	3,000-10,000	200-700	
Strong	S	10,000-20,000	700-1,400	
Very strong	VS	> 20,000	> 1,400	



* Samples of fresh rock material tested to Australian Standards. For rocks showing planar anisotropy, the long axis of the samples is normal to the fabric planes.
† To be defined.
** Some overlap in strength with very strong cohesive soils, e.g., hard desiccated clays. The distinction can be made usually by soaking in water, when soils can be remoulded.

Figure 11. Cracking and disintegration of a stone block induced by microwave energy transmitted from a probe radiator (from Püschner[14]). (Copyright, Centrex Publishing Co., N.V. Philips' Gloeilampenfabrieken, Eindhoven, The Netherlands; reprinted by permission.)

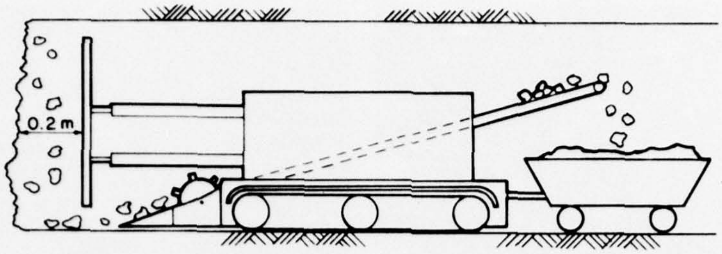
Breakage of competent rock types

The type of breakage that is observed upon irradiating rock is shown in Figure 11.[14] In the rock shown, probe radiators were inserted into holes 15 cm deep and 6.5 cm in diameter. Cracking and disintegration of the rock due to absorption of microwave energy occurred after two minutes. The time of appearance of cracks was found to be dependent on the polarization of the radiation with respect to stratifications in the rock. The nature of the rock was not given. The frequency of radiation was 2.45×10^9 Hz and magnetrons of 5 kw output were used.

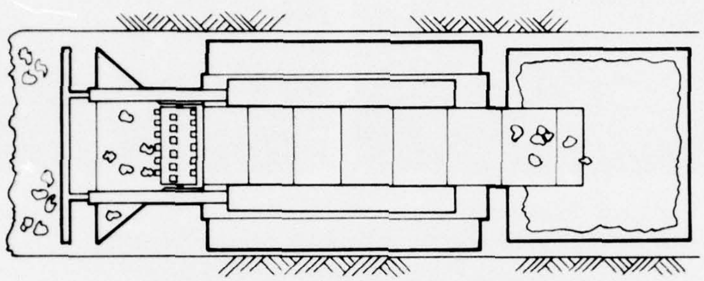
If one speculates about the mechanism causing the cracking of the rock shown in Figure 11, a plausible explanation is to assume that joints and imperfections existed in the rock, and that at these locations electromagnetic radiation was absorbed by films of water, resulting in local heating. The resulting differential thermal expansion lead to buildup of internal stresses, causing the cracking observed.[15] Apparently, these laboratory tests were not performed on different rock types.

A comprehensive series of tests was performed with prototype equipment in a USSR mine.[4] From the brief description in the manuscript based on these tests,[4] the sketch shown in Figure 12 was constructed. The radiator consisted of an antenna, approximately 2 m by 2 m, fed by a coaxial transmission line from a 200-kw magnetron operating at a frequency of 0.5 to 2 GHz (the exact frequency was not given in the report). The antenna was placed 0.2 to 0.3 m from the working rock face and the power was turned on. After one or two minutes, pieces of rock (7 by 5 by 1 cm) began to fall to the floor, where they were removed by a loader. The antenna cutting head was advanced in steps to keep it within 0.2 to 0.3 m from the working face. After a maximum travel of the cutting head (0.4 m) was achieved, the antenna was withdrawn and the machine was repositioned.

These tests were made in a hard rock mine where the composition of the rock varied greatly. As a result of this variation in rock type, a series of tests was made by comparing the behavior of the machine in materials of different strengths. The results of these tests are shown in Figure 13, in which the rates of advance of electromagnetic and mechanical cutting heads are plotted as a function of the compressive strength of the rock. At a compressive strength of approximately 1000 kg/cm^2, equal rates of advance with a mechanical cutter (unspecified) and a cutter using electromagnetic radiation were observed.



a. Side view.



b. Top view.

Figure 12. Sketch of electromagnetic cutting equipment used in a USSR hard rock mine for cutting tunnels of 5-m² cross section.[3]

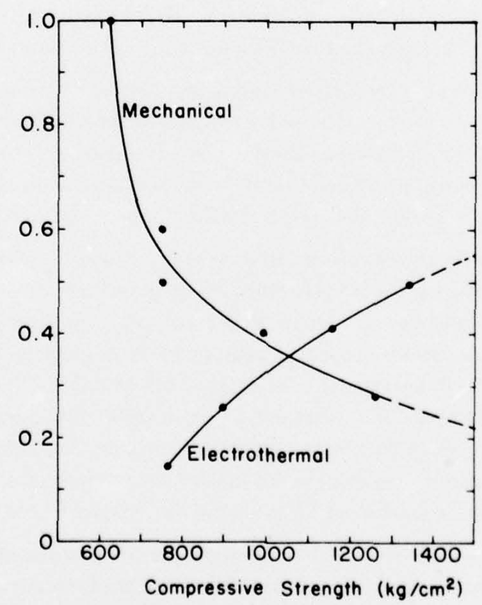
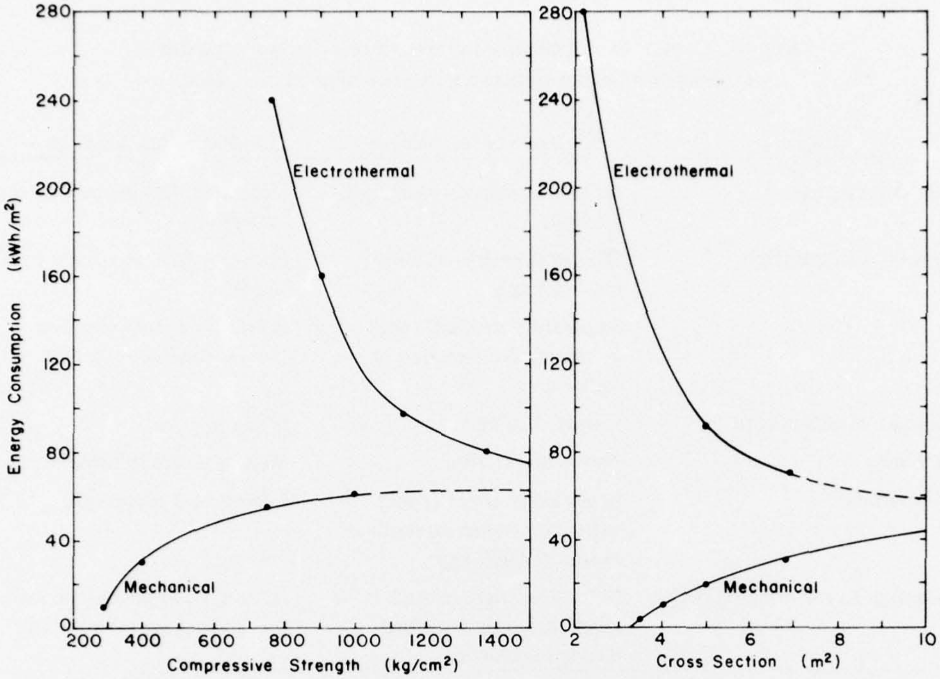


Figure 13. Advance rates of a mechanical cutter and a high-frequency radiator as a function of the compressive strength of rock. The cross section of the rock face was 5 m². (After ref. 4).



a. As a function of compressive strength of rock.

b. As a function of cross section of working face.

Figure 14. Energy consumption (per unit volume) for excavating material by mechanical cutting and by high-frequency electrothermal irradiation as a function of compressive strength of rock and cross section of working face.

Figure 14a compares the power consumption for excavation of a tunnel (cross section 5 m^2) as a function of rock strength. Excavation by electromagnetic means becomes more efficient at higher rock strength, and at a compressive strength of approximately 1500 kg/cm^2, the power requirement of mechanical and electromagnetic cutters are comparable. Figure 14b shows that the energy consumption for electromagnetic cutters decreases with the size of the cross section of the rock face, and that the energy consumption for mechanical cutters increases approximately linearly with the size of the cross section section of the working face. The reason for the decrease in energy consumption with the size of the cross section for the electromagnetic cutters is not stated, but it is probably related to antenna efficiency and radiated power densities.

Several vertical shafts were also excavated in the hard rock mine by electromagnetic means. Antennas were raised to the working face in steps, and the critical components were protected from the falling rock by a screen. The rocks were continuously removed at the bottom of the shaft. When vertical shafts were being cut, the light weight of the radiating antenna gave a decided advantage over mechanical cutters, which are necessarily heavy.

Approximately 50 m of vertical and horizontal workings with cross sections from 2 to 7 m^2 were excavated by using electromagnetic radiation. The conclusions drawn from these tests are summarized in Table III.

Table III. Comparison of electromagnetic and mechanical methods of excavation based on tests in a hard rock mine in the USSR.

Item	*Electromagnetic methods*	*Mechanical methods*
Rate of cutting	Increases with increasing rock strength	Decreases with increasing rock strength
Energy consumption	Decreases with increasing rock strength	Increases with increasing rock strength
	Apparently decreases with increasing cross section of rock face	Is linearly proportional to cross section of rock face
Weight of cutter head	Is light, 120 kg	Is heavy
Bit wear	Shows no bit wear	Wear is severe in competent rock
Versatility	Is workable only in rocks with compressive strength in excess of 1000 kg/m^2	Can be used universally
Damage to surrounding rock	Natural strength of rock is apparently not disturbed during excavation	Natural strength may be disturbed because of vibrations.

Cutting of frozen ground

The strength of frozen ground is to a large extent due to cementation of soil and rock particles by ice; thawing of frozen ground invariably reduces its strength. Frozen ground can be thawed by several means, for example, by steam and electric heating; in both instances heat is transported into the material mainly by conduction. The power densities achieved in this type of heating are typically from 1×10^6 to 3×10^6 w/m^2, and the energy consumption required in thermal excavation was found to be several orders of magnitude larger than that required in mechanical drilling.[7] Russian workers have investigated dielectric heating in frozen ground to obtain high penetration rates and to reduce energy requirements. Frozen ground can absorb energy internally from a high-frequency electromagnetic field; the absorption rate of energy per unit volume is given by eq 6. Figure 4 shows that K'' depends on soil type and temperature, and varies from 0.01 to 4 for frozen ground at 2×10^9 Hz at temperatures from -1° to -10°C. Field strengths up to 3000 v/m are feasible, so that at a frequency of 2×10^9 Hz, power absorption rates may vary from 10^4 to 10^6 w/m^3, which is perhaps of the same order of magnitude as produced in steam and electric heating; the limitations are set by the radiated power densities obtainable with present equipment.

Dielectric heating has an advantage over steam and electric heating in that its energy can, in principle, be focused on a small area by a special radiator (antenna). The concept behind the investigations in the USSR was that frozen ground could be weakened by irradiation and subsequently removed by mechanical action. For example, the radiator shown in Figure 15 was driven by mechanical action into the ground and forced air was used to remove the material between the electrodes. Tests with this device were made on frozen fine-grained materials to cut a slot 20 cm wide. In comparing energy consumption required for complete melting with the experimentally observed rate of penetration, it was found that approximately 20 to 50% of ground was removed (in a frozen state) by forced air. The pressure of the forced airflow was not mentioned, nor did it appear that tests were made at different radiated energy densities.

The maximum rate achieved for cutting a 20-cm wide (depth unknown) slot in frozen fine-grained ground was 0.3 cm/sec, which appears to be below rates possible by mechanical means,

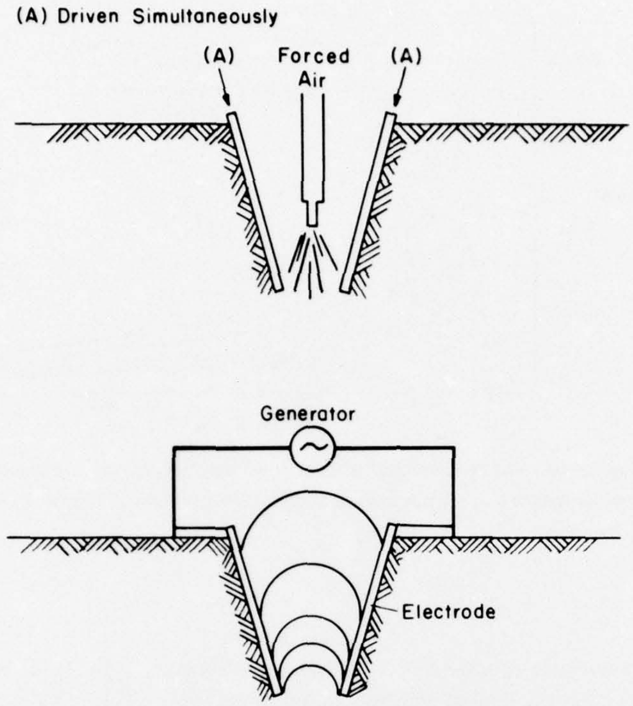


Figure 15. Concept of a tool that combines mechanical energy and electromagnetic radiation, suggested by USSR workers.[10]

which are perhaps as high as 10 cm/sec. In all the tests on frozen ground, there was no evidence of fracturing of ground into small blocks. Excavation of frozen ground seemed to be impossible without the combined use of electromagnetic and mechanical energy, and no evidence was presented to show that this combined use was more efficient in cutting than the use of mechanical energy only.

The reports[8 10] on cutting frozen ground give the impression that the results of laboratory tests were disappointing, but that forced applications are tenuously being sought to justify continuance of the project. For example, to obtain splitting and cracking of frozen ground one publication suggested cooling the surface of a working rock face by liquid nitrogen, so that most electromagnetic energy would be absorbed in the interior, causing local expansion and cracking.

Two reasons may be advanced to explain why electromagnetic heating does not cause the desired fracturing in frozen ground.

1. Melting of ice causes a decrease in volume and probably results in stress relief, rather than the buildup of stresses required for breaking.

2. Absorption of energy occurs in films of unfrozen water, which are probably uniformly distributed throughout the material, so that no intense differences in thermal absorption take place.

In summary, there is at present no evidence in the USSR literature to suggest that the use of high-frequency electromagnetic energy has resulted in economical, high-speed methods for excavating frozen ground.

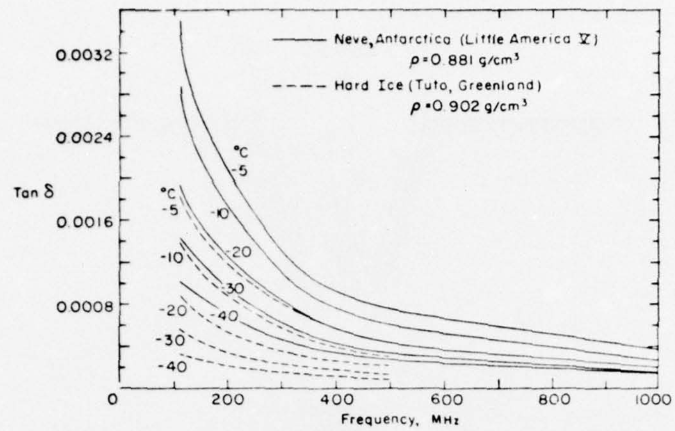


Figure 16. The loss tangent of snow and ice cores from Greenland and Antarctica at several temperatures as a function of frequency (after Waite[17]).

Tests on ice

Freshwater ice does not strongly absorb radiation at microwave frequencies. The loss tangent $\tan\delta$ of cores of ice from Greenland and the Antarctic are shown in Figure 16 as a function of frequency at several temperatures.[17] Based on these data, microwave radiation is not expected to be applicable to the breakage of ice. The absorption of radiation is given by eq 6, so that, in a field of 3 kv/m, at 10^9 Hz, and $K'' = 0.001$, the absorption of energy is 5×10^2 w/m^3.

The rate of melting of a block of ice would initially be less than one part per million per second. The absorption might be two orders of magnitude larger in freshwater ice containing impurities; the energy consumption for melting would also be large.

When specimens (6 by 7 by 3 cm) of polycrystalline ice were placed in very strong electromagnetic fields at frequencies of 13 to 2375 MHz, some interesting observations were made.[11] After 1.5-2.0 sec of irradiation, liquid inclusions and cavities became visible in the ice specimen at the grain boundaries, and after about 10 sec the ice specimen disintegrated into its single crystals. The authors computed that at the time of disintegration approximately 3% of the ice had melted.

Apparently energy was preferentially absorbed by the films of unfrozen water at the grain boundaries; the existence of these unfrozen films is well documented in the literature. It is possible that melting at the grain boundaries occurs only above a certain field strength; and, in the tests, perhaps the field strength was sufficient to exceed breakdown at the grain boundaries.

DISCUSSION

Review of the USSR literature on rock breakage by high-frequency electromagnetic radiation showed that one area of possibly significant application is excavating tunnels and shafts in rocks of high strength. For rocks of low strengths and in frozen ground, the USSR research did not yield promising results. The mechanism that makes use of high-frequency radiation attractive in hard rocks is fracturing caused by thermal expansion some distance behind the air/rock interface. This mechanism, therefore, requires 1) penetration of significant amounts of radiation some distance into the rocks, and 2) concentration of energy absorption at grain boundaries and hairline fractures.

Computations of the effects of radiation as a function of rock type showed that most energy is absorbed at the surface in soft rocks, resulting in very rapid heating of the surface layers, but only small temperature effects beyond the first few centimeters. Computer modeling showed that radiation can penetrate hard rock to depths of 0.5 m, causing gradual temperature rise. The effects of inhomogeneities where energy absorption can be concentrated were not modeled.

In frozen ground, radiation results in melting of the surface layers, and as the Russian results indicate, mechanical tools must remove the thawed surface layers before underlying layers can be exposed.

In general, all investigations lack information on significant parameters, energy absorption as a function of depth, water content, structure, etc. For hard rocks, where both Russian results and computations show that significant applications may occur, it is necessary to conduct a controlled series of laboratory experiments to establish clearly the range of application of the use of high-frequency energy in rock breakage.

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